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PROBABILISTIC LONG-TERM FORECASTS OF MAJOR EARTHQUAKES IN THE SAN FRANCISCO BAY REGION

1984

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**BAY AREA
EARTHQUAKE
STUDY**

The Bay Area Earthquake Project is supported by funding under a Cooperative Agreement between the California Seismic Safety Commission and the Federal Emergency Management Agency. The substance and findings of this work are dedicated to the public. The Bay Area Earthquake Study is solely responsible for the accuracy of the statements and interpretations contained in this publication. Such interpretations do not necessarily reflect the views of the California Seismic Safety Commission, the State of California, or the Federal government.

A Review of Probabilistic Long-term Forecasts for
Major Earthquakes in the San Francisco Bay Region

by

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A Report

to the

Bay Area Earthquake Study

California Seismic Safety Commission

from

The Department of Conservation, Division of Mines and Geology

July 1984

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PREFACE

A principal finding in the first Bay Area Earthquake Study report, "Status of Earthquake Preparedness Programs in the San Francisco Bay Region", reveals that although public awareness of the earthquake risk has been increasing, the scope and magnitude of the problem is not fully understood. Furthermore, that local and regional officials echo these perceptions, lacking a full understanding of the imminence and potential regional impact of a major damaging earthquake in the Bay region. This lack of awareness is partly because engineers and scientists have only very recently gained a more complete understanding of the scope and imminence of the earthquake threat in the Bay Area, and partly because communications between the technical community and the public is limited.

This report reviews the current scientific understanding of the likelihood of future damaging earthquakes in the Bay region, and considers ways in which to effectively convey this information to governmental agencies and the public. The information and recommendations contained in this report are intended to provide a better understanding of the earthquake threat, so that earthquake hazard mitigation programs can establish an appropriate place among other local and regional program priorities.

EXECUTIVE SUMMARY

In the past few years, earthquake activity throughout most of California, including the San Francisco Bay Region, has dramatically increased, reaching a level during which major and even great earthquakes are known to most likely occur. Increasing concern over the prospects of a major earthquake striking a large metropolitan area has led to a growing need to regionally quantify the likelihood of such an event, challenging our knowledge and capabilities in long-term forecasting. Information from such assessments will form the basis upon which many decisions affecting the safety and welfare of society will be made.

Recent research on the seismic behavior of major plate boundaries around the world has provided new insights into the character and processes governing the occurrence of major and great plate-boundary earthquakes. These findings have been applied to the assessment of hazards along the San Andreas and associated faults, which pose the greatest threat to California's major population and industrial centers.

Results of these assessments indicate that although the next "great" ($\sim M8$) earthquake will most likely occur in southern California, repeat times of great earthquakes are known to vary by as much as a factor of two along a given fault segment, emphasizing the need to consider such an event in current earthquake preparedness planning efforts for the Bay area. Furthermore, there is growing evidence that the Bay region has entered the stage when a "major" ($\sim M7$) earthquake can now occur. This threat has been recently underscored by the 1984 $M6.2$ Morgan Hill earthquake, the first $M6+$ earthquake to occur in the Bay region since 1911. Extrapolations of the historical record, assuming a random process, yields odds better than 1 in 2 that a major earthquake will

strike the Bay region in the next 20 years. The current high level of seismicity, together with an observed tendency for large earthquakes to cluster in time, increases these odds and points to the inadequacy of such simple extrapolations. A more deterministic assessment based on detailed fault investigations reveals that Bay area faults having a high probability of rupturing in the next few decades include the segment of the San Andreas from San Juan Bautista to San Jose, and the northern half of the Hayward fault. Both are capable of generating a M6.5 to M7+ event that would cause widespread damage and loss of life.

Probability estimates for individual fault segments do not constitute the likelihood of a major earthquake for the Bay region as a whole. That requires the aggregate probability considering all potential, major earthquake sources which will yield a higher value of probability. Unfortunately, there is insufficient information to allow such an assessment. Consequently, the general question concerning the likelihood of a major earthquake somewhere in the Bay region will remain unanswered from a deterministic point of view, at least until more data on fault offset history becomes available for the other important Bay area faults.

The probability of a major earthquake has not been assessed for the Calaveras fault nor the possible extension of the Hayward fault north of San Pablo Bay. Estimates for these faults, improvements in existing estimates for other faults, and improvements in recurrence models upon which probabilistic forecasts are made must await more detailed investigations along faults known or thought to be capable of producing major earthquakes. The historical record is too brief to provide a complete picture of earthquake occurrences, and disclosure of the prehistoric record through detailed fault investigations is only beginning. Fault movements during the past few thousand years must be known with as little uncertainty as possible if reasonable forecasts of future

activity are to be made. Probability estimates presented in this report, and the assumptions and models upon which they are based, are likely to change as more of this information becomes available. Even given the model assumptions, current probability estimates can be in error by a factor of two or more. This must be kept in mind when using these estimates for decision-making.

Damage scenarios that forecast the impact of a hypothetical great San Andreas earthquake on major lifelines, such as transportation, communication, and energy systems, have been prepared for emergency planning purposes (Davis and others, 1982). A similar scenario is currently being prepared for the Hayward fault. Additional damage scenarios should be developed based on current probabilistic forecasts of other major earthquakes in the Bay region. In addition to lifelines, these projections should include regional assessments of expected damage to single-family dwellings as well as the population at risk.

Long-term probabilistic earthquake forecasts and damage scenarios together constitute basic planning tools to minimize losses. They can be used to set priorities for local, state, and federal spending on earthquake hazard mitigation programs, including: local and regional emergency response and preparedness planning, retrofitting or demolition of hazardous buildings, enforcement of seismic safety codes and ordinances, improved design of new structures, earthquake safety education, and prudent land use planning. Similarly, they can be used to set priorities for scientific investigations related to earthquake hazards. Support of programs to develop these planning tools will, in hindsight, undoubtedly be regarded as a major step toward the reduction of earthquake hazards for many generations to come.

INTRODUCTION

That a major or even great earthquake will again strike the San Francisco Bay area is a foregone conclusion. The real question facing local, state, and federal government decision-makers is when. Loss estimates for a repeat of the great 1906 earthquake run as high as 11,000 deaths, over 40,000 hospitalized, and net property losses of nearly \$40 billion (FEMA, 1981). But, how likely is it for such an event to occur in the next 20 or 30 years? What is the current state of preparedness planning in the Bay area, and where do earthquake mitigation measures lie in local budget priorities?

These and other pertinent questions are currently being investigated by the Bay Area Earthquake Study (BAES), a program created by cooperative agreement between the California Seismic Safety Commission (CSSC) and the Federal Emergency Management Agency (FEMA). This program is aimed at fostering comprehensive earthquake preparedness planning at the regional and local level in the Bay area. Major tasks undertaken by BAES include:

- 1) inventory existing preparedness programs and evaluate their relevancy to future preparedness planning, 2) seek a scientific consensus on the probability of a major damaging earthquake in the Bay area, and 3) develop a work plan for earthquake hazard mitigation and disaster preparedness planning.

This report, prepared by the California Division of Mines and Geology (CDMG), is the second of three reports produced by BAES and addresses the important question of how likely it is that a major earthquake will occur in the Bay area in the next 20 to 30 years. Although a "scientific consensus"

was originally sought, it was recognized early on that a true consensus is premature. The state-of-the-art is such that the first meaningful, quantitative estimates of earthquake likelihood are just now being made.

The past decade of earthquake research has produced many new observations and findings. When taken together, these insights provide a much better model of the earthquake process from which more reliable long-term probabilistic forecasts can now be made. To put such forecasts to practical use, however, requires a clear understanding of the limitations and uncertainties in such estimates. Probabilistic estimates of damaging earthquakes that appear now, or are soon to be in print, vary in methodology, assumptions, results, and reliability, and are likely to be modified in the future as more data on fault-offset history become available. These limitations must be understood if such estimates are to play an effective role in governmental decisions.

This report reviews the state-of-the-art in assessing the odds that a damaging earthquake will occur along a specified segment of a fault during a specified period. It is a review of what might be loosely considered long-term earthquake forecasting. The report is divided into three principal sections. The first section discusses the concept of probability and its use in estimating seismic risk. The second section reviews the current understanding of the earthquake process and what it implies for earthquake recurrence. The third section summarizes recent studies that evaluate the likelihood of future damaging earthquakes in the Bay area. The first two sections are included because it is felt that some knowledge of probability and our current understanding of earthquake recurrence is necessary to more fully comprehend the value and limitations of probabilistic estimates of future Bay area earthquakes.

EARTHQUAKE RISK

Whereas seismic hazard refers to earthquake phenomena that may adversely impact human activities, such as ground failure or strong shaking, seismic risk refers to the probable consequences of such events. Knowledge of the location and character of earthquake hazards must be converted into an estimate of probable cultural impact before government decision-makers, planners, and design engineers can effectively deal with the problem in a practical social and economic sense. Consequently, probability is an important element of seismic risk because it provides insights on the degree of threat which is necessary for setting priorities and determining appropriate levels of action that will be taken to mitigate the hazard.

Although earthquakes are believed to result from a deterministic process of strain build-up and release, the many factors involved in the process renders a strong element of chance in the precise timing of when an earthquake actually occurs at a specific location. This is more commonly the rule than the exception when dealing with natural phenomena. Weather forecasting, as those who have been caught unprepared in an unexpected rainstorm clearly know, is also a game of chance.

Probability is the mathematical science that deals with chance. It provides a means of quantifying likelihood in the outcome of events and is usually expressed as a ratio or percentage. As an example, consider the probability of landing a heads in the toss of a coin. Since there are only two sides (that is, two outcomes), the odds are one in two. This can be expressed as the fraction, $1/2$, or alternatively as 50 percent. The concept of probability becomes increasingly abstract as the number of possible outcomes or number of factors affecting the outcome (the process) becomes

large or complex. A common procedure for estimating the probable outcome of a complex process is to simulate the overall behavior of the process by using a well-known statistical distribution or model. The model parameters and input data are based on actual observations. The value of probability is then computed by the use of standard model formulae and tables. It is important to understand how probability estimates are derived because their value often carries a false sense of numerical preciseness. This is an inherent limitation of quantitative model results, which can be expressed to any desired decimal place but are only as valid as the assumptions upon which they are based.

Inaccuracies in probability estimates can arise from incomplete knowledge of the process involved, whereby false assumptions lead to the selection of an erroneous or inadequate model. Inaccuracies can also arise from uncertainties in the input data to the model. Even when an estimate of probability has low uncertainty, one can still be misled by taking the results too literally and ignoring rare events. Gumbel, a famous statistician, warned of this when he stated: "it is impossible that the improbable will never happen." Because the probability of an earthquake occurring in a particular area might be low does not mean that it will not happen in the time specified, and conversely.

These points are very important to understand when incorporating probabilities into the decision-making process. The next section will review earthquake recurrence as a means of estimating the likelihood of future earthquakes, as well as examine the uncertainties and assumptions in the data and models presently in use.

EARTHQUAKE RECURRENCE

Following the development of the magnitude scale for comparing the relative sizes of earthquakes, it was observed that in a given interval of time, the number of earthquakes in an area increases rapidly as the size, or magnitude, decreases (Table 1). Thus, the time between progressively larger earthquakes, called the recurrence interval, gets progressively longer. This characteristic of earthquake occurrences is known as the Gutenberg-Richter Law. As a consequence of this law, one must consider the size of the event when addressing the question of how often it occurs.

Although moderate earthquakes can cause damage, major and great events are usually considered for regional emergency response planning. This class of events can cause severe damage over large multi-jurisdictional geographic areas (Table 1). If one knows when the last earthquake of this size occurred, a recurrence model can provide a means of estimating the likelihood of a reoccurrence at some specified future time. Before discussing various recurrence models currently in use it is useful to review, in a simplified way, the current understanding of the earthquake generating process.

According to Plate Tectonic Theory, the crust of the earth consists of a dozen or so large, rigid plates that slowly move about the earth's surface, independently driven by gravitational, rotational, and thermal forces within the earth's interior. Interaction of these plates along their boundaries generate stresses that deform the adjacent terrain for hundreds of kilometers. California is a very seismically active region because it is transected by the San Andreas fault (SAF), a major plate boundary that separates the Pacific and North American plates.

TABLE 1. Size Classification of Damaging Earthquakes

Qualifier	Magnitude Range	Number ¹	Area ²
Great	> 7.5	1	> 40,000
Major	6.5 - 7.5	4	3000-40,000
Large	5.5 - 6.5	45	200- 3,000

1. Number of occurrences in the Bay region since 1800.
2. Area, in square kilometers (Toppozada, 1975), shaken at intensity VII on the Modified Mercalli scale (Wood and Neumann, 1931). This corresponds to slight, moderate damage in well-built buildings, and considerable damage to poorly built or badly designed buildings.

Earthquakes are caused by the sudden release of elastic energy stored in crustal rocks. Stresses acting within the terrain gradually build over time until the strength of the rock is exceeded and it breaks, generating seismic waves that travel through the ground over long distances. Ground breakage occurs along faults, where the rocks on either side suddenly slip past one another. The greater the amount of slip and the longer the rupture, the larger the earthquake. Over long periods of geologic time (millions of years), the accumulated slip along a fault from many repeated events can be tens or even hundreds of kilometers.

Slip along the SAF accounts for only about 60 percent of the relative plate motion between the Pacific and North American plates. The remainder is presumably taken up by slip along other faults, as well as folding of rocks over a broad zone hundreds of kilometers wide either side of the SAF plate boundary. Slip rate is the average annual slip along a fault, which for the SAF is about 3 cm/yr. During the past 10 million years, the SAF has displaced terrain on either side, some 300 km or more. As it continues to do so, great earthquakes like the 1857 Fort Tejon and 1906 San Francisco events will continue to occur.

Stochastic Recurrence Models

Although earthquakes result from a deterministic process of strain accumulation and release along faults, large regions often contain many active faults that appear to act independently, resulting in a random pattern of earthquake occurrences with time. In such large geographic areas, earthquake occurrences can be considered a stochastic process (governed by chance). A random occurrence of events can be characterized by what is called a Poisson

distribution, which has been successfully used to model many temporally random processes such as the number of telephone calls received by an exchange or the number of traffic accidents at a given intersection in a specified interval of time.

A Poisson distribution is completely described by the mean rate of event occurrence. Knowing the mean rate of occurrence of earthquakes greater than M6.5 in the San Francisco Bay region, for example, permits estimating the probability that a major event will occur in a prescribed interval of time. The implicit assumption, however, is that events of such size occur randomly with time over the region (figure 1, Table 2). Table 3 shows the mean rate of occurrence of earthquakes in the San Francisco Bay region based on the 180-year historical record shown in Table 2. Using a Poisson model yields a probability of 54 percent, or odds of about 1 in 2, that a major event will occur in the next 20 years somewhere in the Bay area (Table 3).

While this estimate might be useful for certain aspects of regional planning, if we attempt to apply this method to individual faults in an effort to localize the problem, the assumption of randomness breaks down and the method fails. To address this problem, a deterministic approach must be used.

Deterministic Recurrence Models

Earthquakes are a product of the build-up and sudden release of strain along a fault or zone of weakness in the earth's crust. At the instant an earthquake initiates, the crustal rocks within the zone have reached an initial state of stress that exceeds their shear strength. Failure of the rock, characterized by slip along the fault, is accompanied by a marked reduction in stress to a lower, "final" state of stress. Shimazaki and Nakata

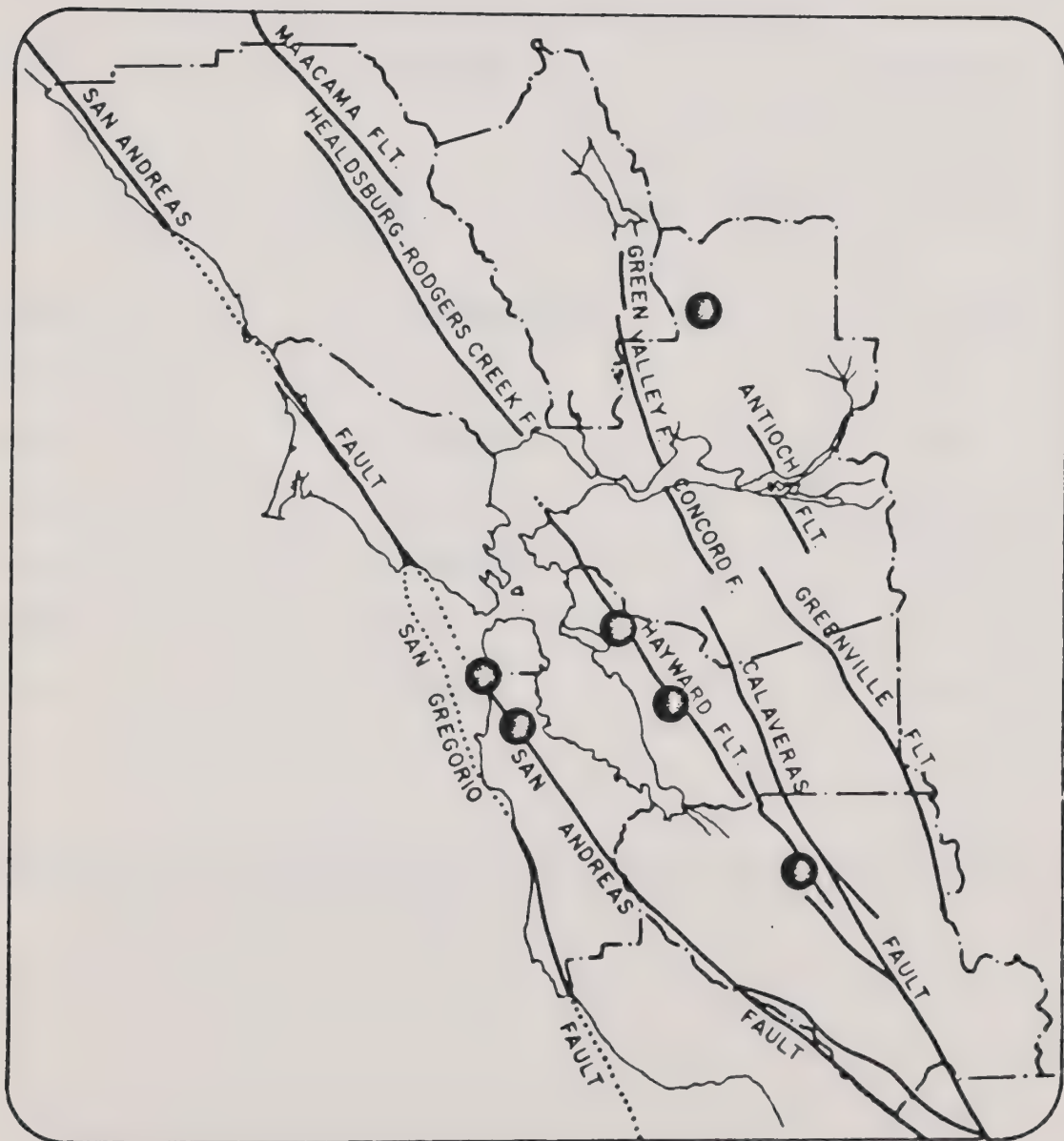


Figure 1. Principal faults and major historical earthquakes in the San Francisco Bay Region.

TABLE 2. Major Earthquakes in the San Francisco Bay Region
from 1800 to 1984.

DATE	LOCALITY	MAGNITUDE
Jun 1808	SAN FRANCISCO	(VIII)*
Jun 1836	HAYWARD	6.8
Jun 1838	WOODSIDE	7.0
Oct 1868	HAYWARD	6.8
Apr 1892	WINTERS	6.4
Apr 1906	SAN FRANCISCO	7.8
Jul 1911	COYOTE	6.6

* Cracked walls of houses and destroyed an antichamber at the Presidio.

TABLE 3. Probability of a Major Earthquake in the San Francisco Bay Region in the next 20 - 30 years based on a Poisson Model.

Observation Period ¹	Mean Rate (events/yr)	P (next 20 years)	P (next 30 years)
180 years	.04	54%	69%
104 years	.07	74%	87%

1. Shown are two intervals; the shorter spans the period of high activity that includes by the earliest and most recent major earthquakes (table 2), while the longer spans the entire historical record.

(1980) proposed three alternative models to describe the stress history along a fault (figure 2). Each of these models is illustrated by a sawtooth diagram showing stress along the vertical axis and time along the horizontal axis. Each tooth on the curve represents a cycle of stress relief corresponding to an earthquake occurrence. Stress is assumed to accumulate at a constant rate in all three models as indicated by the ramp having a constant slope. As time progresses, the failure stress is eventually reached (point of the tooth); the ground breaks and the earthquake occurs, accompanied by an instantaneous drop in stress indicated by the vertical segment of each curve. The cycle then begins over again.

The first recurrence model is called "simple periodic" or "characteristic earthquake" (figure 2a). This model is characterized by a constant initial stress (failure) and a constant final stress over several earthquake cycles. This corresponds to a constant stress drop and associated slip as indicated by the vertical lines on the sawtooth curve. Consequently, each earthquake generated by a stress relief cycle is the same size and has a constant repeat time; hence, the name "characteristic earthquake." If the earthquake process perfectly obeyed this model, knowledge of the initial and final stress states, the rate of strain accumulation, and when the last event occurred would permit forecasting both when and how large the next earthquake would be.

The second recurrence model, called "time-predictable," is very similar to the first except that the final state of stress is not constant but instead varies in an unpredictable way with time (figure 2b). With this model, knowledge of how large the last event was and the rate of strain accumulation permits estimating when the next event will occur but not how large it will be.

The third recurrence model is called "slip-predictable," and differs from the other two in that only the initial stress varies in an unpredictable way

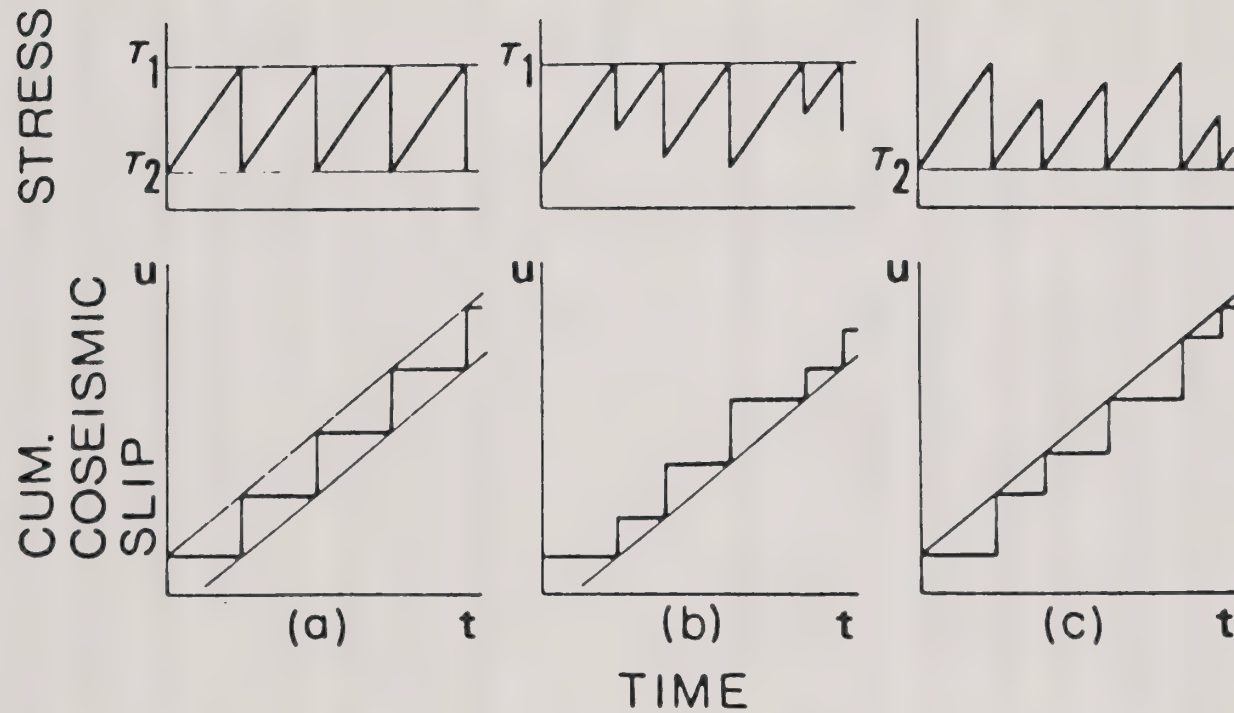


Figure 2. Deterministic recurrence models: a) simple-periodic, b) time-predictable, and c) slip-predictable. Upper curves show stress accumulation with time (τ_1 initial-failure stress, τ_2 final stress). Lower curves show accumulated fault slip with time (Shimazaki and Nakata, 1980).

with time (figure 2c). Knowledge of the time elapsed since the last event and the rate of strain accumulation permits estimating how large an event would be but not when it will occur.

A fourth model might be characterized by variation of both the initial and final stress with time under constant loading. Such a model might be appropriately called a "random" recurrence model, since neither the size nor the time of occurrence is predictable in a deterministic manner.

Analysis of the historical earthquake record and detailed studies of pre-historic offsets along major fault zones lend some support to the "characteristic earthquake" and "time-predictable" recurrence models (Shimazaki and Nakata, 1980; Mogi, 1981; Wesnousky et al., 1983; Schwartz and Coppersmith, 1984; Scholz, C.H. 1984). There is presently insufficient evidence, however, to completely preclude the other models.

Hybrid Recurrence Models

A recent approach to estimating the likelihood of earthquakes along major plate boundaries combines the "characteristic" recurrence model with a statistical model to account for variance about the average recurrence time (Brookshire and Schulze, 1980; Lindh, 1983; Jacob, 1984; Sykes and Nishenko, 1984). Thus, rather than assuming earthquake recurrence to be strictly periodic, allowance is made for the fact that an event usually occurs before or after the time expected from the average recurrence interval. This can result from nonlinear strain accumulation caused by variations in plate motions, complex interactions of fault blocks, or, possibly, by a controlling influence of large and major earthquake occurrences by great earthquakes. The uncertainty about the average recurrence time has been modeled by two

statistical distributions: the "normal" and the so-called "Weibull" distributions.

The normal distribution is the familiar symmetrical, bell-shaped curve that represents the distribution of measured values or occurrences about an average value, such as random errors in the measurement of the length of an object (figure 3). With probability along the vertical axis and the parameter of interest along the horizontal axis, the curve shows the probability of observing a particular value. The peak of the bell-shaped curve marks the highest probability and is centered over the average value. Therefore, for normal distributions, the average is the most probable value.

The Weibull distribution, named after the Swedish mathematician who devised it, has been used to describe the uncertainty in the timing of failure for materials under load. The curve looks very similar to the normal except that it is more peaked. Its use in failure theory, as applied to manufacturing quality control, suggests application to the earthquake process which is, after all, a manifestation of crustal failure. As will be described in the next section, the input data to these models presently have a high degree of uncertainty, and use of models more sophisticated than the normal distribution are probably unwarranted at this time.

Fault Displacement History

As evident from the preceding discussion, average recurrence time is an important parameter for long-term earthquake forecasting. Estimates of the average recurrence interval along individual faults, or fault segments, are based on historic and pre-historic occurrences of earthquakes. Because recurrence intervals for major earthquakes appear to fall in the range from

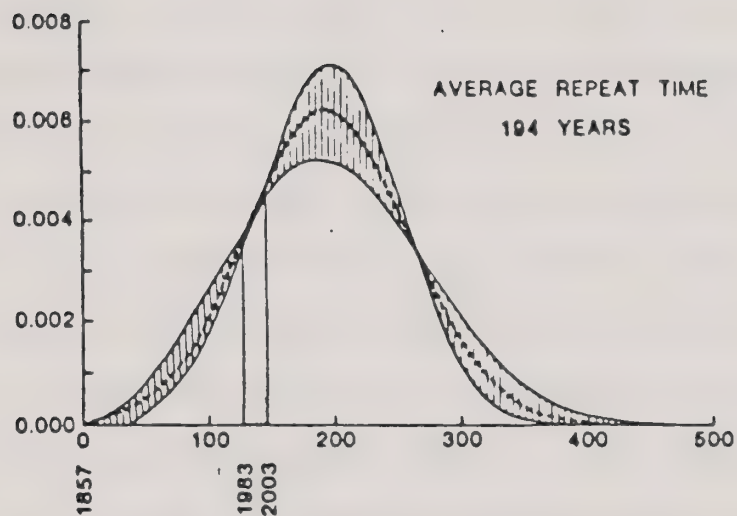


Figure 3. Normal (dashed) and Weibull (solid) distributions for recurrence data on the San Andreas fault near Pallett Creek (Sykes and Nishenko, 1984).

hundreds to thousands of years, the historical record is simply too brief to permit reliable average estimates. Indeed, of nearly all the damaging earthquakes that have occurred in California during historic times, few have ruptured the same fault segment twice. One can further deduce that the historical record is too brief to have sampled even one major earthquake on some active faults. For faults such as these, the entire historic record may only be a portion of the interval between the last major earthquake and the next one yet to come. Thus, we cannot rely on the historical record alone to estimate recurrence times of major, or even large, earthquakes.

In an effort to overcome the inadequacies of the historical record, Wallace (1970) presented an alternative method of estimating recurrence time that is based on the average slip rate along a fault. If one assumes that seismic slip along a fault (slip independent of fault creep which is unaccompanied by earthquakes) results from repeated earthquakes of about the same size and associated displacement, then dividing the displacement by the average slip rate will yield the amount of time required to accumulate sufficient strain to produce the earthquake. For example, if the average displacement associated with a major earthquake on the SAF is 4 meters, an average slip rate of 3cm/yr would yield an average recurrence time of about 133 years for such events. Expressed another way, along those segments of faults that intermittently lock rather than continuously creep at a uniform rate, earthquakes large enough to produce 4 meters of slip would occur at an average interval of 133 years in order to accommodate a slip rate of 3cm/yr. Use of this method requires that both the average slip rate and average displacement be known.

Average displacement can be estimated from historic earthquake occurrences or from ancient fault scarps or discrete fault offsets observed in

the adjacent rocks. Slip rate is either measured by repeated surveying, usually referred to as geodetic slip rate, or by measuring offset geologic formations, sediments, or soils of a known age, referred to as geologic slip rate. Use of long-term geologic slip rates provide a means of incorporating a longer seismic history into the estimates of average recurrence intervals.

Average recurrence interval can also be estimated by identifying discrete offsets in exposed rocks, sediments, or soils of a known or determinable age along the fault zone, thereby extending the earthquake record back to pre-historic times. This can also be done, though less reliably, by identifying datable artifacts in adjacent sediment layers that are associated with particular earthquake occurrences such as sedimentary features caused by shaking. Sieh (1978) extended the record of major earthquakes on the SAF near Palmdale, California back some 2,000 years by this technique, thus enabling for the first time estimates of the average recurrence interval along that segment of the SAF.

Information on the history of faulting is difficult to obtain. Suitable sites along the fault zone must be found that contain evidence of pre-historic earthquakes in the stratigraphic record. Experience has shown that such sites are difficult to find. Once found, the site must then be drilled or excavated to reveal the special features used to identify past events and amounts of fault offset. The rock or soil units must then be dated in order to permit rates of offset or time intervals between events to be determined. Because the special rock or soil features are difficult to recognize and interpret, such studies are very prone to individual biases. This, combined with the difficulty in obtaining reliable dates, results in uncertainties that can exceed the value of the recurrence interval itself. However, recurrence estimates based on slip rate or pre-historic offsets are still considered more reliable than those obtained from the historical record alone.

This section has provided a brief summary of the approaches and uncertainties associated with earthquake recurrence. The next section will summarize the results of several recent investigations in the San Francisco Bay area that address the probability of future damaging earthquakes in the region.

PROBABILITIES OF MAJOR EARTHQUAKES IN THE BAY AREA

Extensive studies of seismicity along major plate boundaries around the world have recently led to new insights into the process and variations of strain accumulation and release along these major faults. Rocks on either side have been found to slip past one another with little or no resistance nor associated seismic activity. In other cases, the rocks bind along discrete zones that are referred to as "asperities". It is here where the resistance to slip causes strain to accumulate, eventually resulting in an earthquake. This markedly different character has been observed to occur along different segments of the same fault. For example, repeat times of large earthquakes can vary by a factor of ten from one fault segment to another, as can the size of the largest event expected for a particular segment. There is an increasing body of evidence, however, that suggests the size of an event remains relatively constant for a segment. That is, fault segments along major plate boundaries may have characteristic earthquakes. These findings are being applied to hazard assessment along the SAF throughout California.

In a reassessment of the earthquake hazard in California, Bolt and Jahns (1979) concluded that the odds are about 1 in 2 that a major earthquake will occur somewhere in California in the next decade. Their assessment was based primarily on the historical record of major earthquakes, which have an average

recurrence interval of about 15 years in California as a whole. They noted that by 1979, it had been 27 years since the last major earthquake in California, and that if no such event occurs by 1989, the interval will have grown to 37 years; longer than any other interval between major earthquakes in historic time. Considering the 166-year recurrence interval for the southern segment of the SAF that ruptured in 1857, they concluded that similar recurrence intervals for the northern and southern extremities of the SAF imply that the SAF, taken as a whole, would have a recurrence time of about 70 years for a major earthquake. Extrapolating this reasoning to all other California faults capable of producing major earthquakes, they further concluded that the historical record's 15-year recurrence interval is in agreement with the probable longer-term record. Although according to Bolt and Jahns the odds are 1 in 2 that the next major earthquake will occur by 1990 somewhere in California, these odds consider the entire state and, consequently, do not apply to the Bay area alone. Furthermore, because the data set used to derive their estimates includes the 1922 Cape Mendocino earthquake, one might conclude that their forecast has been fulfilled by the 1980 M7.0 Eureka earthquake that occurred offshore, ending a 28-year period of major earthquake quiescence.

To better forecast the next major earthquake that would most severely impact major California metropolitan areas, Raleigh and others (1982) focused on the SAF, dividing it into four segments extending from the Gulf of California to Cape Mendocino based on apparent independent behavior of each segment in recent geologic and historic time. Considering the slip rate and the time and size of the last event for each fault segment, they qualitatively concluded that the southern California extent of the SAF will most likely rupture next in a great earthquake, and that it could do so at any time.

During an exhaustive study of earthquakes that occurred in California before 1900, Toppozada and others (1978) concluded that the comparatively higher level of seismic activity before than after the 1906 earthquake may have been premonitory. This historic pattern of large and major earthquakes to cluster prior to the great 1906 earthquake can be easily demonstrated by recomputing the Poisson probability of occurrence as before, only this time using the time interval bracketed by the first and last major earthquake shown in Table 2, rather than the entire historical record. Because this interval does not include the 70 years of quiescence since 1911, the probability has increased from 54 percent to 74 percent for a 20-year interval, and from 69 percent to 87 percent for a 30-year interval. This simply reflects the fact that the mean rate of occurrence was higher before the great 1906 earthquake than it was after (Table 3). From this, one can conclude that the occurrence of major earthquakes in the Bay region is not random in time, and that a Poisson model is probably inappropriate.

Ellsworth and others (1981) recognized that this pattern is very similar to that observed for great earthquakes along the highly seismic margin of the western Pacific, and concluded that the strain relief cycle of great earthquakes along the SAF appear to have a controlling influence on the occurrence of moderate, and even large, earthquakes in the Bay region. They also concluded that although a return of the great 1906-type earthquake may be decades away, the increase in seismic activity at the M5 level since 1955, which ended the long quiescence since 1906, suggests that the Bay region is entering an active stage of the cycle during which major earthquakes can again occur. Evidence in favor of this forecast continues to mount up, as indicated by the recent M6.2 Morgan Hill earthquake, the first M6+ earthquake to occur in the Bay region since 1911.

Bufe and Topozada (1981) noted that the high level of seismic activity throughout California in recent years, including the 1979 M6.6 Imperial Valley, the four 1980 M6+ Mammoth Lakes, and the M7.0 offshore Eureka earthquakes, clearly indicates that California has emerged from a period of seismic quiescence that followed in the 1950's. Recognizing that great plate boundary earthquakes tend to occur during periods when the frequency of moderate-to-large earthquakes increase, Raleigh and others (1982) have concluded that the dramatic increase in California seismicity in the past few years has increased the prospects for a major earthquake in California to an annual probability of about 13 percent. During the time following these investigations, this extraordinary increase of seismic activity in California has continued. Two damaging earthquakes (1983 M6.6 in Coalinga and 1984 M6.2 in Morgan Hill) have occurred, reinforcing the concern that a major earthquake might strike a metropolitan area in the near future.

To quantitatively estimate the likelihood of future major earthquakes in the immediate Bay region, several investigators have used the semideterministic (hybrid) recurrence model previously discussed. This model was first applied to the SAF in southern California by Brookshire and Shulze (1980), in their economic assessment of the effectiveness of earthquake hazard mitigation programs. Dividing the SAF into segments in a manner similar to Raleigh and others (1982), two research groups, working independently on the west coast (Lindh, 1983) and the east coast (Sykes and Nishenko, 1984), applied hybrid recurrence models to each fault segment and arrived at remarkably similar results. Their estimates are state-of-the-art, and constitute the most complete probabilistic hazard assessment along the SAF to date. Both have assumed that the SAF can be meaningfully divided into individual segments, and that each segment ruptures with a characteristic earthquake.

The results of these two studies are shown in figures 4 and 5, which have been reproduced from their original reports. Although we are primarily interested in those fault segments impacting the Bay region, it is useful to compare probabilities for these segments with other fault segments in southern California. It is important to note that while both studies assessed the entire SAF, the scope of each study differed in that Lindh also assessed the Hayward fault, while Sykes and Nishenko assessed the Imperial and San Jacinto faults. The first notable similarity between the results of the two studies is the way in which the SAF is segmented. This might be expected since both studies based their analysis primarily on the existing body of knowledge regarding past behavior and characteristics of the SAF. The results are also of the same order of magnitude, and, considering the factor of two or more uncertainty, are nearly the same from one fault segment to the next.

Sykes and Nishenko (figure 4) have chosen to separate estimates based on historic and pre-historic ruptures from those based only on the last occurrence and slip rate. Estimates based on the latter are believed to have a greater uncertainty.

Probability estimates for major earthquakes in the Bay region have been extracted from these two studies, and are shown in Tables 4 and 5. The estimated size of the characteristic earthquake for each segment of the SAF is nearly identical for the two studies. Clearly, the San Juan Bautista segment is the most probable to rupture in a major earthquake in the near future, with an annual probability of a few percent per year. The Hayward fault also appears likely to generate a major earthquake in the not too distant future. For comparison, results of a probability assessment by Coppersmith (1983) for the Hayward fault is shown in Table 6. Though his results are projected over the next 5 and 50 years, they are in general agreement with those of Lindh

ANNUAL EARTHQUAKE PROBABILITIES for selected fault segments of the San Andreas Fault System

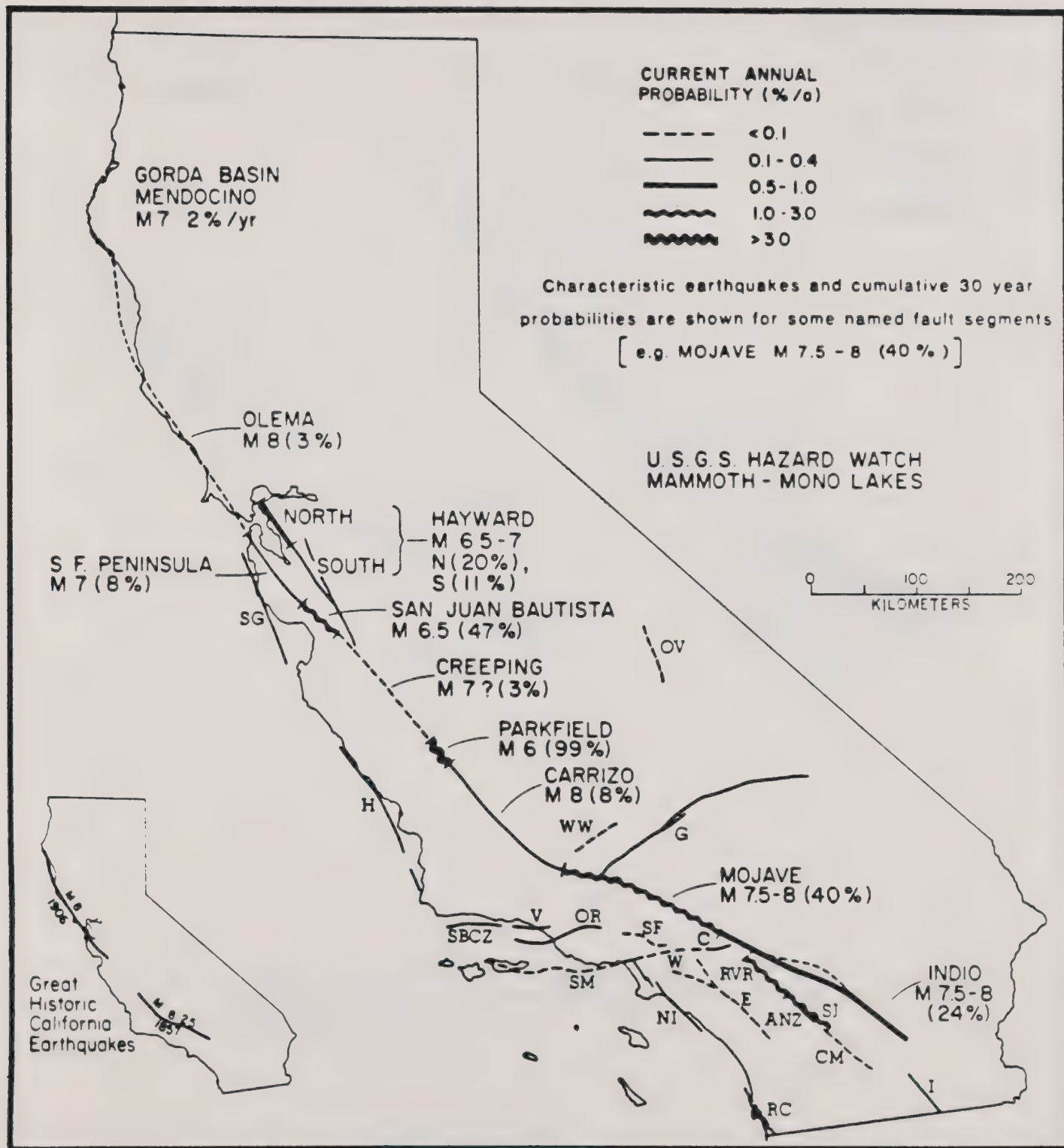


Figure 4. Probabilities of major earthquakes along the San Andreas and Hayward faults (Lindh, 1983).

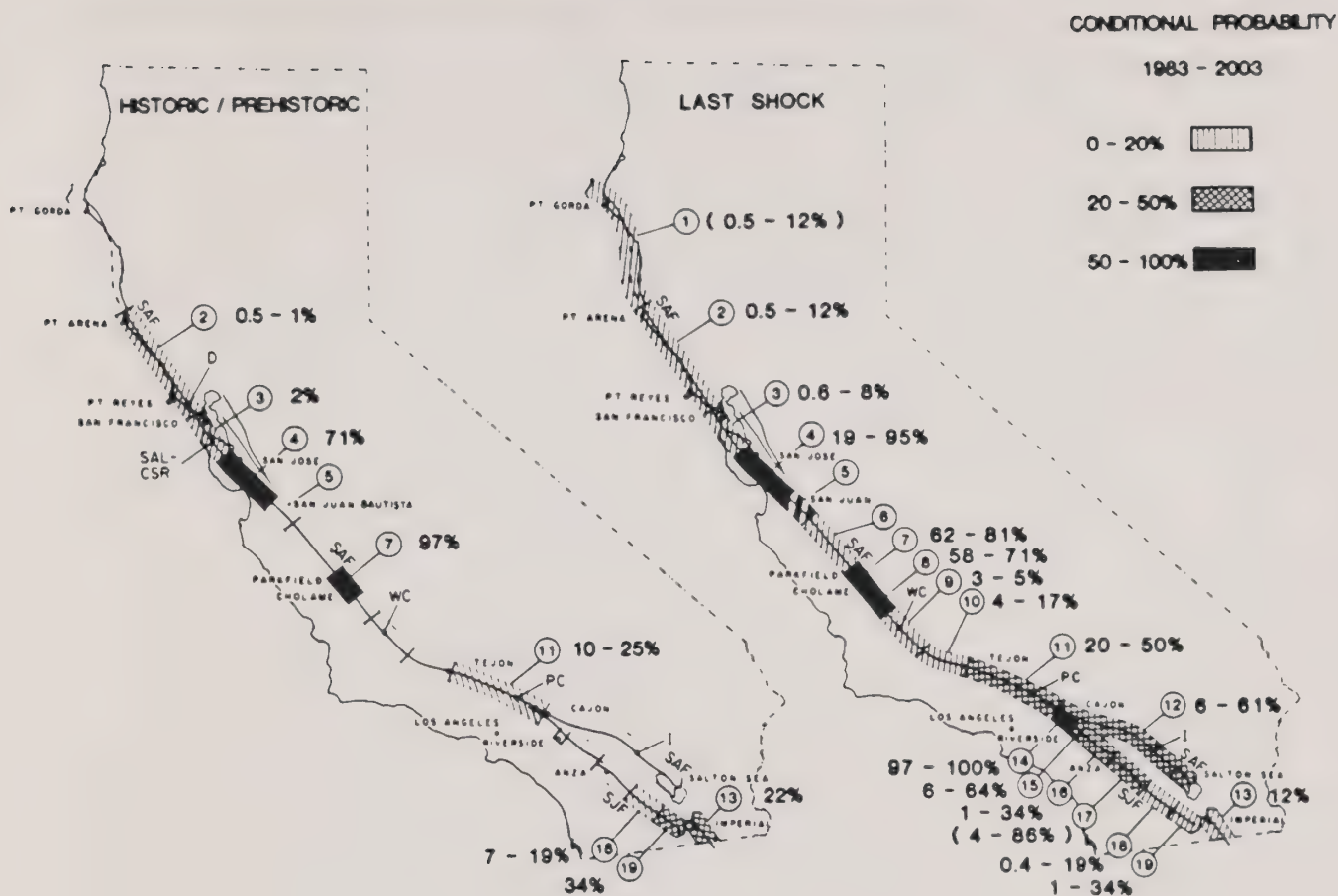


Figure 5. Probabilities of major earthquakes along the San Andreas, San Jacinto, and Imperial faults (Sykes and Nishenko, 1984).

(Table 4). To illustrate the influence of slip rate on probabilistic estimates using the last occurrence to estimate repeat time, Coppersmith presents estimates for slip rates of 3 mm/yr and 6 mm/yr.

TABLE 4. Probabilities of major earthquakes in the San Francisco Bay Region in the next 20 years From Sykes and Nishenko (1984).

Fault segment ¹	P(Hist/Prehis)	P>Last shock)	Magnitude
SAF SAN JUAN BAUTISTA	71%	19-95%	7
SAF PENINSULA	2%	.6- 8%	7
SAF - OLEMA	.5-1%	.5-12%	8

TABLE 5. Probabilities of major earthquakes in the San Francisco Bay Region in the next 20 and next 30 years From Lindh (1983).

Fault Segment ¹	P (next 20 years) ²	P (next 30 years)	Magnitude
SAF - SAN JUAN BAUTISTA	30-64%	47-83%	6-1/2
SAF - PENINSULA	5-14%	8-23%	7
SAF - OLEMA	2-7%	3-12%	8
HF - NORTH	12%	20%	6-1/2-7
HF - SOUTH	7%	11%	6-1/2-7

1. SAF - San Andreas fault; HF - Hayward fault.
2. The range in probability for each segment corresponds to the disparity between results based on geologic and those based on geodetic data.

TABLE 6. Probabilities of major earthquakes along the Hayward fault in the next 5 and next 50 years from Coppersmith (1983).

SLIP RATE	P (next 5 years)	P (next 50 years)	M
3 mm/yr	12%	59%	6-1/2
	1%	14%	7
6 mm/yr	19%	96%	6-1/2
	6%	26%	7

Unfortunately, the slip rate along the Hayward fault is not well known, as is the case for most other faults capable of producing a major earthquake. Estimates of the long-term slip rate vary from about 5 mm/yr to 10 mm/yr. Presently, it appears that most of the slip along the Hayward fault is occurring as creep, unaccompanied by seismic activity (Prescott and Lisowski, 1981). It is not known whether creep was occurring at the time of the M6.8 1868 earthquake. Consequently, the range of probability estimates in Table 6 give some idea of their uncertainty.

It is in the area of detailed fault investigations that future work is most urgently needed. More reliable estimates of recurrence probabilities must await more plentiful and better constrained estimates of slip rate, number and amounts of past displacements, and average recurrence intervals along principal earthquake producing faults during the past few thousand years. Such information will not only produce more stable estimates from the various models, but will also help determine which of the existing recurrence models is most appropriate, or perhaps even lead to improved models. Until these data can be gathered, it is unlikely that improvements will be made over the results reviewed here for the Hayward and San Andreas faults. Probabilistic assessments remain to be made for the Calaveras fault and for other faults north of San Pablo Bay. These assessments must await detailed fault investigations, for the long-term behavior of these faults as well as variation of character along their extent is presently unknown.

CONCLUSIONS

The dramatic increase in seismic activity throughout California is characteristic of when major, and even great, earthquakes are known to occur. Application of new insights into the recurrence of great plate-boundary events has been used to assess the probability of major earthquakes along the San Andreas fault system in the next 20-30 years. Although the probability of a repeat of the Great 1906 earthquake is only a few percent, a segment of the San Andreas fault from San Juan Bautista to Los Altos has a probability of about 50-70% that it will produce a major earthquake in the next few decades. Similarly, the northern and southern segments of the Hayward fault have probabilities of about 20% and 11%, respectively. Although these estimates may be in error by as much as a factor of two, they are, nonetheless, very sobering.

In order for local officials and the public to fully understand the full implications of estimates such as these, the results must be presented in a more uniform and simplified way. The information presented should be useful, understandable, and complete enough to fully convey the hazard status. For example, the probability of generating a major earthquake could be estimated for uniform intervals, perhaps decades, over the next 50 years for those faults having sufficient data. This would provide the earthquake likelihood for various exposure periods while also illustrating the increase in hazard with time. Probability would perhaps best be expressed as odds, as it is often done by the news media when discussing the likelihood of disease. Odds can be further simplified by grouping under low, moderate, and high probability.

An effective way of providing a more meaningful context in which to interpret earthquake probabilities is to compare them with other common risks

that one has a more intuitive feel for. For example, the long-term probabilities presented here correspond to annual probabilities (the probability that an event will happen in any given year) of a few percent. Expressed in this way, it enables one to compare the annual risk of a major earthquake with that of other types of accidents that can occur in day-to-day experiences. For this purpose, Table 7 has been reproduced from the report of Brookshire and Schulze (1980). As indicated, the probability of a major earthquake occurring in the Bay region is roughly equivalent to the probability of sustaining injury from an accident at home, or being injured in a motor vehicle accident sometime during the course of a year.

A full understanding of the earthquake threat requires not only the likelihood of the event occurring, but also the consequences. Damage scenarios, describing the earthquake's impact on major lifelines and the population, should accompany probability estimates for each fault or fault segment rupture. This could be effectively done by adding a section on event probability to the format of current damage scenarios (Davis and others, 1982).

Damage scenarios and long-term probabilistic earthquake forecasts are basic planning tools to reduce losses. The long-term forecasts reviewed in this report are an important step toward providing these tools. More fault investigations are needed to improve these estimates, and the recurrence models upon which they are based. More fault investigations are also needed to provide estimates of slip rate and offset history for the Calaveras fault, as well as extensions of the Hayward fault north of San Pablo Bay. Data on the current geodetic slip rates, long-term geologic slip rates, and creep rates must be collected and compared for all Bay area faults capable of generating damaging earthquakes, in order to more accurately assess rates and amounts of accumulated strain. These data will ultimately lead to a more

reliable and complete assessment of the likelihood of future damaging earthquakes in the San Francisco Bay region. Until such investigations are made, the probability estimates reviewed in this report will remain the best presently available.

Table 7. EXAMPLES OF RISKS/YEAR

Probability of a major event on the San Andreas Fault this year	= 1.2%
Among all urban dwellers,	
probability of serious injury from accidents at home	= 1.96%
probability of death from accidents at home	= .13%
Among all manufacturing and nonmanufacturing workers,	
probability of a disabling injury from accidents at work	= 2.765%
probability of death from accidents at work	= .018%
Among all California residents,	
probability of death in motor vehicle accidents	= .025%
probability of death in other accidents and by violence	= .057%
Among all licensed drivers in the U.S.,	
probability of injury in motor vehicle accidents	= 1.8%
probability of being in a motor vehicle accident involving property damage	= 22.7%
probability of being killed in a motor vehicle accident	= .049%
Among all U.S. residents,	
probability of death or injury as an airline passenger:	
catastrophic probability of death	= .0002%
accidents probability of injury	= .0001%
ordinary probability of death	= .0001%
accidents probability of injury	= .0014%
Among all U.S. residents,	
probability of death by disease:	
	<u>25-44 age group</u> <u>45-64 age group</u>
heart	.041% .445%
cancer	.039% .285%

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